LETTERS TO THE EDITOR

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Communications should not in general exceed 600 words in length.

On the Stability of Stellar Neutron Cores

The quite regular variation of stellar energy generation with stellar mass has seemed to justify the hope that neither the structure nor the mechanism of energy generation would differ essentially from star to star. With increased knowledge of the rates of nuclear reactions, it has grown clear that such reactions must take place in stellar interiors, and that, on the basis of a standard Eddington model, reactions must occur which can account in order of magnitude for the radiation of the lighter stars. In particular it would seem that the formation of deuterons by proton collision, and at the least partially regenerative capture of protons by elements between carbon and oxygen could be made to account successfully for the main sequence stars.[1] Nevertheless it has been clear that these reactions could in no way account for the enormously greater radiation of such stars as Capella, and that for these either one would have to invoke other and readier nuclear reactions, with a correspondingly reduced time scale, or one would here be led, as in the earlier arguments of Milne, to expect serious deviations from the Eddington model.

It is in this connection that the suggestion[2] of a condensed neutron core, which would make essential deviations from the Eddington model possible even for stars so light that without a core a highly degenerate central zone could not be stable, still seems of some interest. Essential for a discussion of the role of such a core, is the estimate of the minimum mass for which it will be stable. An estimate of Landau, based apparently on the requirement that the sum of the gravitational and kinetic energies per particle of core should be lower than the energy per particle in stable nuclei (Landau chose oxygen), led to the value 0.001 solar masses for the limiting mass. This figure appears to be wrong; if one takes only gravitational attraction into account, the binding energy of a neutron in the core does not become equal to nuclear binding energies until the core mass is about $\frac{1}{3}$ that of the sun. It is true that Landau's requirement is unnecessarily severe: In order that the core be stable with respect to the most firmly bound nuclei (say calcium) it is only necessary that the neutron's free energy in the core be less than that in the nucleus. Since the total core energy is proportional to the 7/3 power of the number of particles, the magnitude of the free energy in the core is 7/3 the mean binding energy. One thus gets a limiting core mass of $\frac{1}{6}$ that of the sun. It seems that these results can be obtained without serious error by assuming a uniform density for the core: The actual polytrope gives only a slightly greater stability (roughly ten percent).

A core of this high mass, even in a star considerably more massive than the sun, would involve a complete breakdown in the Eddington model, since so heavy a core would be surrounded by a degenerate zone which would use up the star's total mass. The question of the actual stability of core models thus involves a consideration of the contribution of nuclear forces to the core-binding. The forces which must be known are those acting between a pair of neutrons; and no existing nuclear experiment or theory gives a complete answer to this question. If, however, we assume that the forces between neutrons are of the spin exchange saturating type $(\sigma\cdot\sigma')$, they help to reduce the lower limiting mass for core stability only to about $\frac{1}{10}$ that of the sun; the degenerate zone surrounding such a core must have nearly the sun's mass; and thus if such a core existed, the Eddington model would be completely wrong except perhaps for very massive stars.

If, on the other hand, one gives up the requirement of saturating two body forces and accepts an explanation of saturation along the lines of the suggestion of Critchfield and Teller,[3] he will be led to suppose that the forces between all pairs of nuclear particles are, except for Coulomb forces, the same, and that the only important factor making the binding energy of a neutron in the core smaller than in say a Ca nucleus is the increased kinetic energy which the promotion required by the exclusion principle involves. With this assumption the minimum core mass is very much reduced, and a mass of a few percent of that of the sun would insure its stability. For core masses under 0.03 that of the sun, the mass of the degenerate zone will be less than that of the core.

It seems clear that even in the heaviest stars no core will be formed until practically all sources of nuclear energy have been, at least for the central material of the star, exhausted. The arguments given above cannot, therefore, be regarded as showing that, even with the most favorable assumption about nuclear forces, actual stars have cores; but they do show that forces of the often assumed spin exchange type preclude the existence of a core for stars with masses comparable to that of the sun.

J. R. Oppenheimer
Robert Serber

Department of Physics,
University of California,
Berkeley, California,
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[1] Bethe and Critchfield, Phys. Rev. **54**, 248 (1938). We are indebted to Dr. Bethe for an interesting discussion of these questions.
[2] Gamov, *Atomic Nuclei and Nuclear Transformations*, second edition (Oxford, 1936), p. 234. Landau, Nature **141**, 333 (1938).
[3] Critchfield and Teller, Phys. Rev. **53**, 812 (1938).